Steel bar – concrete bond behaviour in the context of the ETS shear strengthening technique for RC beams

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Abstract: The use of near-surface mounted (NSM) technique has been proved to be very effective to increase the flexural and shear resistance of reinforced concrete (RC) beams. However, the NSM is not applicable for the shear strengthening of RC slab, thus a new technique was developed (ETS – Embedded Through-Section), consisting in opening holes across the slab thickness in the shear zone, where bars are inserted and bonded to concrete by an adhesive material. To assess the contribution of the bond mechanism for the shear strengthening effectiveness of this technique, a comprehensive pullout test program was carried out, where the influences of the type of adhesive, a thickness of the adhesive layer, diameter of the strengthening bar and bond length on the bond phenomena were assessed. The experimental program is described and the obtained results are presented and analysed in this paper.

Keywords: Strengthening, shear, ETS, steel, concrete.

1. INTRODUCTION

The use of near-surface mounted (NSM) technique is a promising technology to increase the flexural and shear strength of deficiently reinforced concrete (RC) members. However, in some cases, the effectiveness of the NSM technique for the flexural strengthening of statically indeterminate slab strips was limited due to the occurrence of shear failure at the hogging region. In case of slabs, the NSM shear strengthening technique is not applicable, which has motivated the development of a new shear strengthening technique that can be suitable for RC slabs and beams. This technique consists in opening holes across the slab thickness in the shear zone, where bars are introduced and embedded with an adhesive material (embedded through section, ETS, technique).

Since the strengthening bars are inserted into holes open through the cross section, they are much better protected from fire, environmental aggressive agents and vandalism acts than externally bonded reinforcement (EBR) and near surface mounted (NSM) techniques based on the use of fiber reinforced polymer (FRP) systems. This research program has started in 2007, where the use of FRP and steel bars, applied according to a technique that was originally designated by Core Drilled Mounted (CDM), was explored for the shear strengthening of concrete elements. In this context, direct shear tests were executed with the

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purpose of capturing the main features of FRP/Steel CDM bars for the shear resistance, and to provide data for a rational decision about the most effective bars and adhesives for this type of application [1]. From the results, a significant increase in shear strength was obtained with a relatively low reinforcement ratio, and it was verified that steel bars were very effective.

To assess the bond contribution mechanisms for the shear strengthening effectiveness of this technique, an experimental program of pullout tests was carried out, where the influence on the bond behavior of the adhesive type (two epoxy-based adhesives) and the thickness layer of the adhesive (2 mm and 5 mm when using strengthening bars of 8 mm; 2 mm, 4 mm and 6 mm for the 12 mm diameter steel bars) was assessed. The experimental program is described and the obtained results are presented and analyzed in this work.

2. SPECIMENS

The geometry of the pull out test specimens is shown in Figure 1 and was based on recommendations given by RILEM/CEB/FIP [2] and on experimental programs described in other publications [3-5]. The typical test specimen consisted of a concrete block with 15x15x20 cm3 in which a steel anchor bar was embedded in its center.

The specimens were divided into two series, S1 and S2, in correspondence to diameter of the steel bar, 8 mm and 12 mm, respectively. Each series includes two groups, one for each adhesive type. Since adhesives have an important role on the effectiveness of this strengthening technique, specimens strengthened with two different adhesives were tested, namely two distinct types of epoxy-based bond agents (S&P Resin 50 and Sikadur 32N).

The test specimens in each group have two different embedment lengths: 50 mm and 75 mm. Table 1 resume the full experimental program. Each specimen is designated by a set of symbols and numbers to be uniquely identified. The notation adopted to identify the specimens is AX_DY_LZ_TW-N; AX_DY_LZ_TW-N, where X is the type of adhesive (X=K for Sikadur and X=S for S&P; Y is the diameter in mm: Y=8 or 12; Z is the bond length in mm: Z=50 or 75; W is the thickness of the adhesive layer in mm: W=2, 4 or 6 and N is number of sample: 1 or 2). Therefore, AK_D8_L50_T6-1 denotes the type of adhesive (Sikadur), D8 represents the steel bar diameter (8 mm), L50 indicates the embedded length of 50 mm, T6 corresponds to a layer thickness of 6 mm and 1 denotes the first specimen out of the two replicates.

3. MATERIALS PROPERTIES

Table 2 includes values obtained from experimental tests for the characterization of the main properties of the materials used in the present work.

Adhesive Type	Series						
	S1 (8 mm)			S2 (12 mm)			
	Hole diameter (mm)	Layer thickness (mm)	Embedment length (mm)	Hole diameter (mm)	Layer thickness (mm)	Embedment length (mm)	
Sikadur 32N (S)	12	2	50	16	2	50	75
				20	4		
	18	5		24	6		
S&P Resin 50 (E)	12	2		16	2		
				20	4		
	18	5		24	6		

Table 1 - Details of the experimental program.

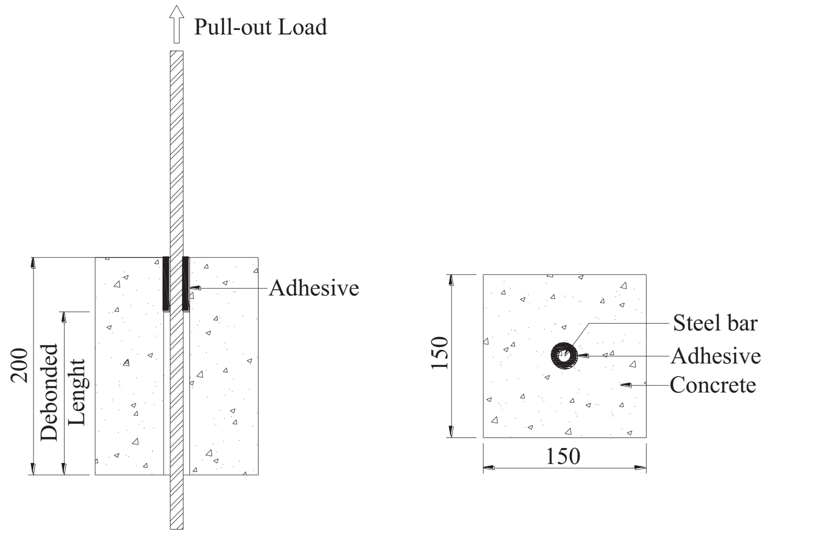


Figure 1 - Geometry of the specimens (all dimensions in mm).

Steel bars					Epoxy Adhesive			
					Sikadur 32N		S&P Resin 50	
Diameter (ϕs)	Young´s Modulus (GPa)	Yield stress (0.2 %)[a] (MPa)	Strain at yield stress[b]	Tensile strength (MPa)	Tensile strength (MPa)	Young´s Modulus (GPa)	Tensile strength (MPa)	Young´s Modulus (GPa)
8 mm	200.80 (2.33%)	421.35 (0.53%)	0.0023 (2.65%)	578.75 (0.36%)	26.29 (10.62)	3.94 (9.82)	26.83 (4.62)	1.60 (4.64)
12 mm	200.46 (0.75%)	449.44 (1.06%)	0.0022 (1.72%)	589.62 (0.77%)				

[a]Yield stress determined by the "Offset Method", according to ASTM A370 (2002)

[b]Strain at yield point, for the 0.2 % offset stress

(value) Coefficient of Variation (COV) = (Standard deviation/Average) x 100

Table 2 - Summary of the properties of steel bars and epoxy adhesives.

Cylinder specimens with a diameter of 150 mm and a height of 300 mm were used to obtain the compressive strength and the Young's modulus according to LNEC-E397 [6]. The average compressive strength (fcm) and the static modulus of elasticity in compression (Ec) were determined at the age of 28 days. For the concrete, an elasticity modulus and average compressive strength of 29.83 (0.29) GPa and 28.40 (1.61) MPa were obtained, respectively, where the values between round brackets correspond to the standard deviation.

To characterize the steel bars, uniaxial tensile tests were conducted according to the standard procedures of ASTM A370 [7]. For the characterization of the tensile behaviour of the epoxy adhesive, uniaxial tensile tests were performed complying with the procedures outlined in ISO 527-1 [8] and ISO 527-2 [9]. Two types of epoxy adhesive were used: Sikadur 32N and S&P Resin 50, formed by two components.

4. SPECIMENS PREPARATION AND STREGTHENING

The first step of the strengthening process consisted in opening the holes for the installation of the steel bars, by using a conventional diamond-coated drill. Compressed air was used to remove the dust generated during drilling. The anchors were made of 8 mm or 12 mm diameter steel bars. These bars were cut to the desired length, wire brushed and wiped clean with a cloth saturated with acetone to remove any residue.

The holes had a diameter that varied between 12 mm and 24 mm. The drilled holes were filled with the epoxy adhesives (Sikadur and S&P Resin 50) and then the steel bars were installed. The adhesive thickness was 2 mm and 5 mm for the steel bars with 8 mm diameter and 2 mm, 4 mm and 6 mm for the steel bars with 12 mm diameter (Table 1). The embedment lengths were 50 mm and 75 mm.

To ensure that any adhesive flowing down did not form an extra bond between the steel and concrete, a plastic tube was applied over the part of the bar to be unbounded length (Figure 2). The pull-out tests were executed when the adhesives have been cured at least 16 days. The pull-out tests were executed at the laboratory environmental conditions, according to the set-up illustrated in Figure 3.

Figure 2 - Jacketing of the steel bar with a plastic tube to obtain the unbounded length.

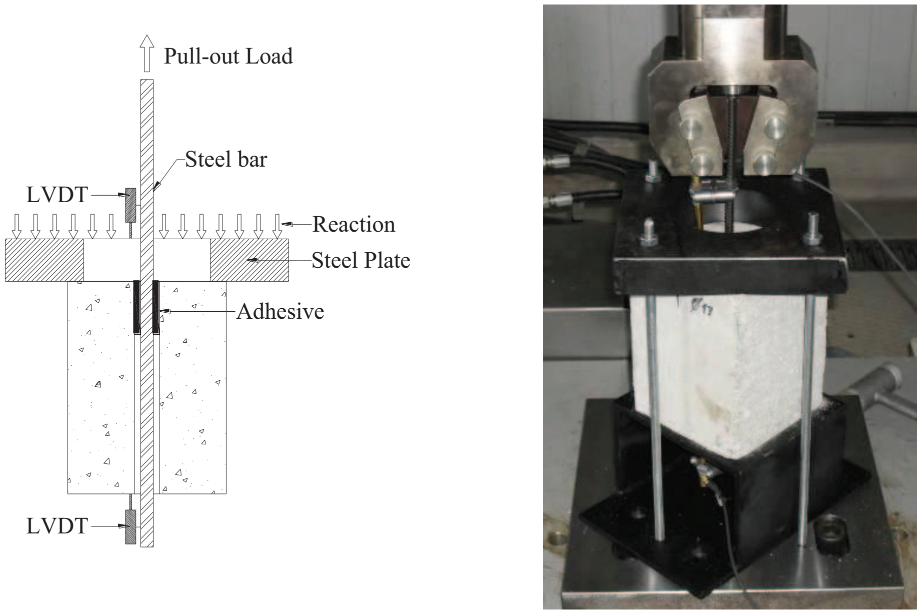


Figure 3 - Pull-out test setup.

5. RESULTS AND DISCUSSION

The strengthening or rehabilitation of structures by adding glue between reinforcing steel bars and the concrete requires special attention to the interface between these materials. The influence of the adhesive layer thickness and the bond length on the behavior of the strengthened specimens is analyzed. During the pull-out test the bond stress profile changes along the embedment length [10], but the main focus of the present research was not to assess the local bond law and its dependence on the parameters investigated. To derive a practical design indicator, the influence of the parameters analyzed was restricted to the average bond stress that is defined as (it is assumed that the bond strength is constant along the bond length):

$$\tau = \frac{F}{\pi d_b l_b} \tag{1}$$

Where F is the tensile load applied to the bar, d_b is the bar diameter and l_b is the embedment length. The variability of the results can be attributed to the small size of the specimens and the adhesive bond length, since a minor variation in their length may lead to a large variation in the results. Thus, the measurement of the bond length of each specimen was performed after each test. It should be noted that the specimen AS_D8_L50_T5-1 presented a bond length lower than expected due to poor positioning of the steel bar.

The relationship between the average bond stress and the slip between the bar and the concrete (at loaded and free ends) is used to analyze the bond behavior. The experimental results obtained from the bond tests are indicated in Table 3. In this table, $F_{\max}$ is the maximum pull-out force, $\tau_{\max}$ is the bond strength (bond stress at $F_{\max}$), ε_s is the strain in the steel bar at $F_{\max}$, and $s_{m,l}$ and $s_{m,f}$ are the loaded and free end slip at $F_{\max}$, respectively. The average value of the bond strength for the replicated specimens ($\bar{\tau}_{\max}$) is also indicated.

The global behavior of the bond stress–slip relationship is characterized by an initial ascending part with an almost linear response, followed by a nonlinear branch with slippage amplitude that increases with the layer thickness of the adhesive. After bond strength has been attained a softening regime occurs with a decrease of the bond strength with the increase of the slip. The relationships between the bond stress and the slip at the loaded and free ends for each tested specimen are shown in Figures 4 to 6. A resume of the tests is also presented in Figure 7.

5.1 Influence of the type of adhesive on the average bond strength

For the strengthening of RC structures by bonding the concrete substrata to an intervening material, it is necessary to choose the best type of adhesive that suits the aimed goal. Thus, there is a large number of formulations on the market in order to obtain the better response of the adhesive according to its mechanical properties and specifications of application. As aforementioned, two types of epoxy adhesive were used: Sikadur 32N (K) and S&P Resin 50 (S), formed by two components.

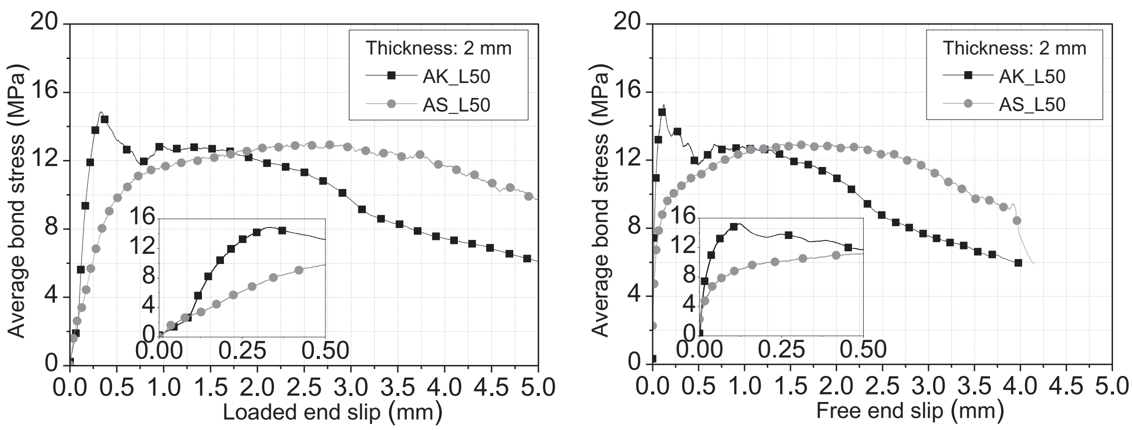
The relationship between the average bond stress and the slip up to bond strength is stiffer for the K bond adhesive than for the S adhesive, which is justified by the higher elasticity modulus of the former adhesive.

Apart the $\bar{\tau}_{\max}$ obtained for the specimens AK_D12_L50_T4-1 and AK_D12_L50_T4-2, the specimens bonded with K bond adhesive developed higher $F_{\max}$, and consequently, higher $\bar{\tau}_{\max}$. Since both K and S adhesives have similar tensile strength, this feature provided by the adhesive is justified by the larger elasticity modulus of the S adhesive. In fact, this particularity of this adhesive has provided larger resistance to the sliding process of the bar due to the higher confinement provided by the micro-compressive-adhesive struts formed during the pullout process [11].

	Specimen	At the specimens testing age (days)		l_b (mm)	Adhesive layer thickness (mm)	F_{max} (kN)	τ_{max} (MPa)	ε_s (‰)	$\bar{\tau}_{max}$ (MPa)	$s_{m,l}$ (mm)	$s_{m,f}$ (mm)
		Specimens	Adhesive								
S1 (8 mm)	AK_D8_L50_T2-1	190	23	50	2	21.79	17.34	0.09	-----	3.14	1.53
	AK_D8_L50_T5-1	195	28	48	5	20.19	16.74	0.08	-----	1.67	-----
	AS_D8_L50_T2-1	188	21	50	2	15.89	12.64	0.06	-----	1.91	1.36
	AS_D8_L50_T5-1*	184	17	28	5	9.43	13.40	0.07	-----	2.23	1.63
S2 (12 mm)	AK_D12_L50_T2-1	223	21	48	2	29.78	16.46	0.07	14.40	0.38	0.15
	AK_D12_L50_T2-2	223	21	52		24.18	12.33			0.33	0.11
	AK_D12_L50_T4-1	223	21	50	4	23.74	12.59	0.06	11.40	1.83	1.35
	AK_D12_L50_T4-2	223	21	51		19.63	10.21			0.23	0.12
	AK_D12_L50_T6-1	223	21	51	6	30.19	15.70	0.07	14.85	0.75	0.35
	AK_D12_L50_T6-2	223	21	52		27.42	13.99			0.92	0.73
	AK_D12_L75_T2-1	223	21	75	2	46.42	16.42	0.07	14.45	0.63	0.12
	AK_D12_L75_T2-2	223	21	76		35.75	12.48			0.40	0.13
	AK_D12_L75_T4-1	223	21	73	4	42.02	15.26	0.07	14.81	0.70	0.53
	AK_D12_L75_T4-2	223	21	76		41.16	14.36			0.16	0.09
	AK_D12_L75_T6-1	223	21	76	6	39.93	13.94	0.07	14.32	1.80	1.25
	AK_D12_L75_T6-2	223	21	75		41.53	14.69			1.33	0.98
	AS_D12_L75_T2-1	220	18	53	2	19.28	9.65	0.06	13.01	2.60	2.00
	AS_D12_L75_T2-2	220	18	50		30.86	16.37			2.51	1.63
	AS_D12_L75_T4-1	218	16	53	4	26.07	13.04	0.06	12.59	0.60	0.72
	AS_D12_L75_T4-2	218	16	56		25.62	12.13			0.62	0.49
	AS_D12_L75_T6-1	220	18	56	6	28.59	13.54	0.07	13.40	1.09	0.75
	AS_D12_L75_T6-2	220	18	60		30.02	13.27			1.28	0.05
	AS_D12_L75_T2-1	220	18	72	2	28.59	10.53	0.06	11.18	0.61	0.51
	AS_D12_L75_T2-2	220	18	77		34.29	11.82			3.24	2.32
	AS_D12_L75_T4-1	218	16	75	4	37.77	13.36	0.06	12.75	0.72	0.43
	AS_D12_L75_T4-2	225	23	82		37.50	12.13			0.94	0.80
	AS_D12_L75_T6-1	220	18	76	6	40.49	14.13	0.07	13.47	1.49	1.00
	AS_D12_L75_T6-2	220	18	78		37.63	12.80			0.43	0.40

* Bond length lower than expected due to poor positioning of the steel bar

Table 3 - Results from the experimental program.



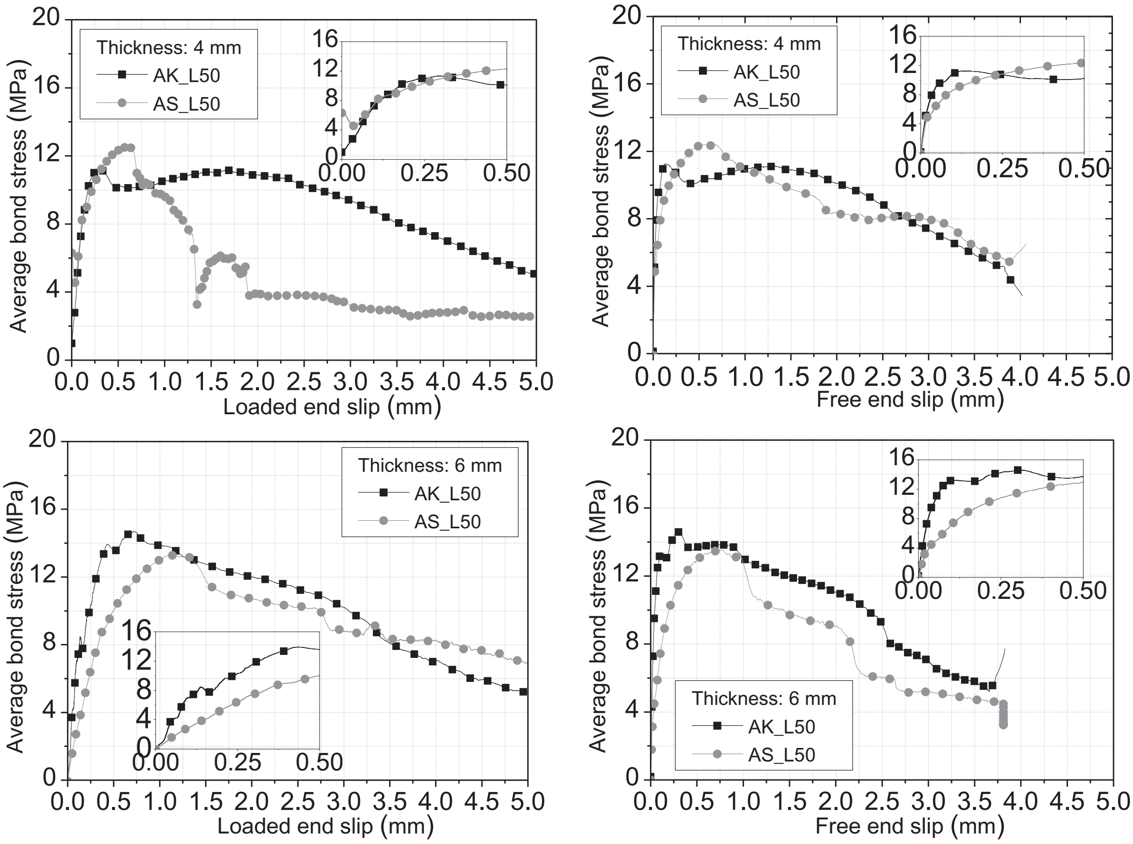
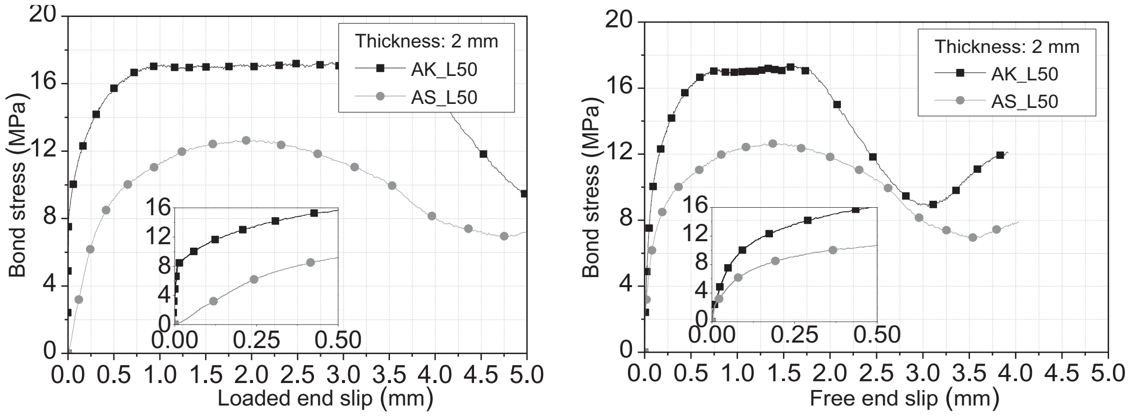


Figure 4 - Influence of the type of adhesive on the average bond stress vs slip at the loaded and free ends for the specimens with a bond length of 50 mm and bar diameter of 12 mm.

5.2 Influence of the strengthening bar diameter on the average bond strength

The results presented in Figures 4 to 7 and in Table 3 indicate that, in most of the tested specimens, the bond stress decreased with the increasing of the strengthening bar diameter. Tests conducted by Meszaros (apud [12]) also showed similar behavior to the ones obtained in this experimental program.



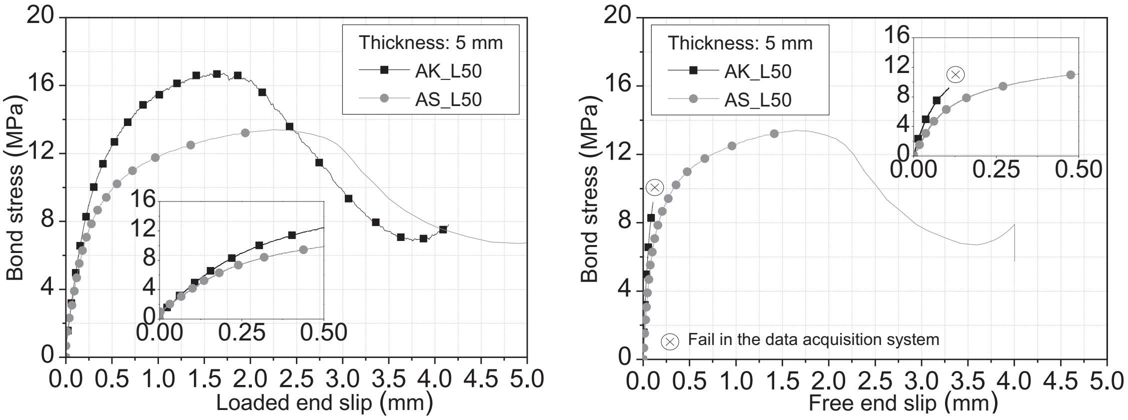
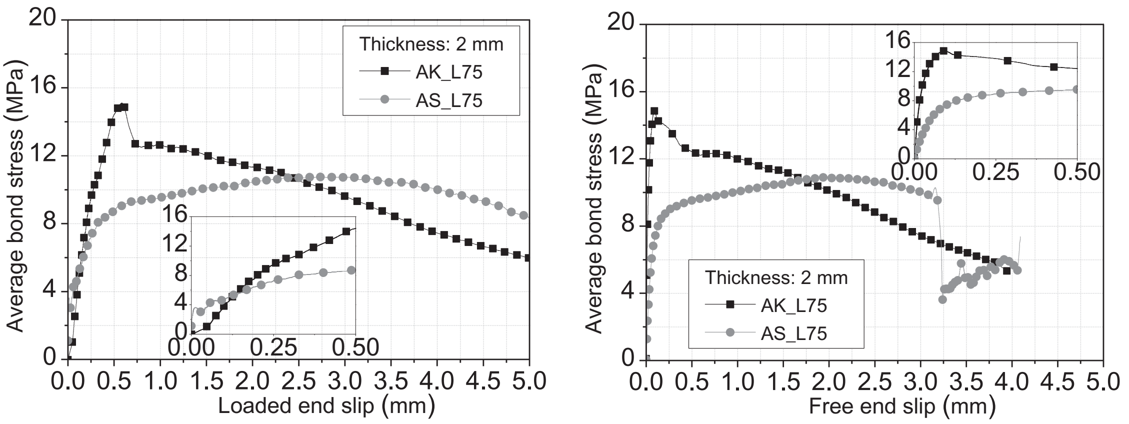


Figure 5 - Influence of the type of adhesive on the average bond stress vs slip at the loaded and free ends for the specimens with a bond length of 50 mm and bar diameter of 8 mm.

5.3 The effect of adhesive layer thickness on the bond strength

The bond stress in the interface between concrete/epoxy and adhesive/strengthening bars was investigated as a function of adhesive thickness. Two different adhesive thicknesses were adopted to the strengthening of the specimens with bars of 8 mm diameter: 2 mm and 5 mm. Concerning to the specimens strengthened with bars of 12 mm, three adhesive thickness were tested: 2 mm, 4mm and 6mm (Table 1).

According to the results, the specimens strengthened with a steel bar of 8 mm diameter (S1) exhibited similar behavior regardless the thickness of the adhesive. An average bond stress of 13.02 MPa and 17.04 MPa were obtained for the S and K bond adhesives, respectively.



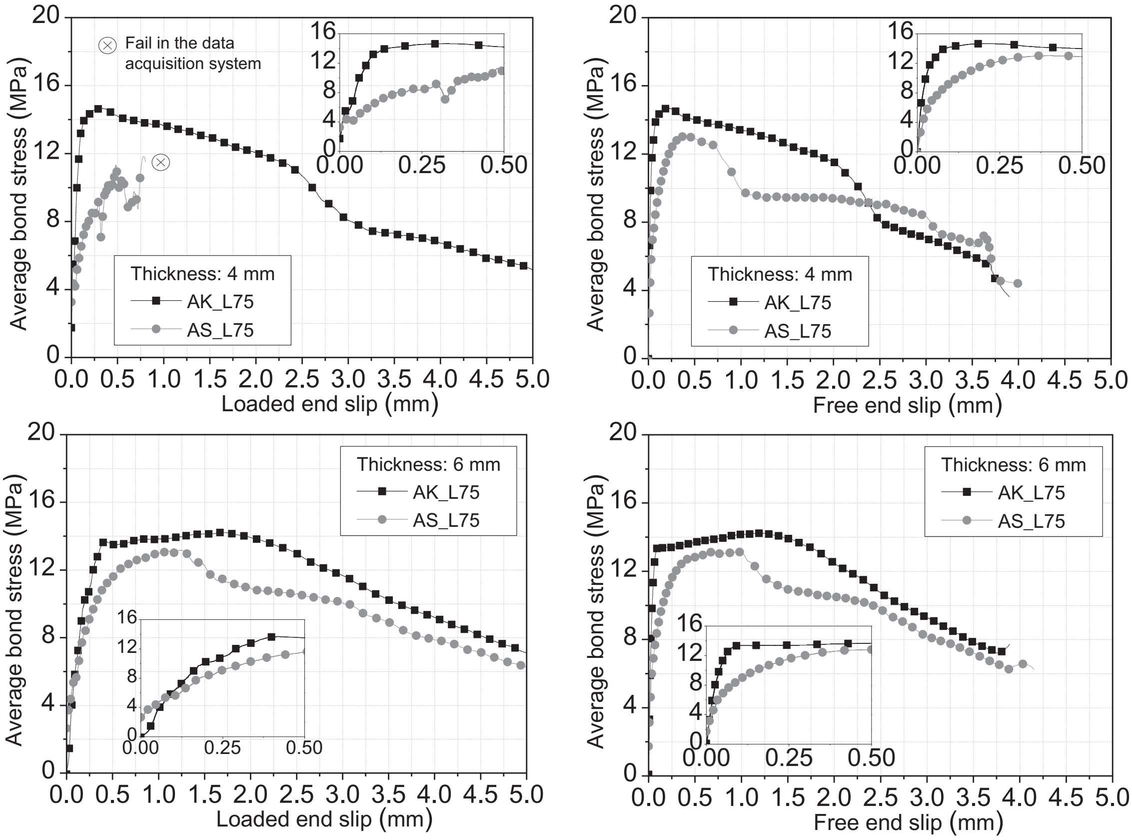


Figure 6 - Influence of the type of adhesive on the average bond stress vs slip at the loaded and free ends for the specimens with a bond length of 75 mm and bar diameter of 12 mm.

In general, when using a steel bar with 12 mm diameter (S2), the maximum bond stress did not present an evident variation when increasing the adhesive layer thickness. For a very thin adhesive thickness, 2 mm, epoxy systems has provided average shear stress values of 14.04 MPa (1.31) and 12.74 MPa (0.87) for K and S bond adhesives, respectively, where the values between round brackets correspond to the standard deviation. As the adhesive thickness increases, the average bond stress of both systems is similar to the results obtained for the adhesive thickness of 2 mm, except for the AK_D12_L50_T4 specimens, which presented a lower bond stress (11.40 MPa). Resuming, for the considered thickness values of the adopted adhesives, the adhesive shear strength was not significantly affected by the layer thickness of the adhesive.

5.4 The effect of embedment length on the bond stress

To assess the influence of the embedment length on the maximum bond stress, two different embedment lengths were tested: 50 mm and 75 mm. The relationship between the average bond stress and the embedment length is represented in Figures 4 to 9. It was expected an increase of load with the embedment length. However, in general, the strengthened specimens reached similar average bond stress. From these data, no influence of the embedment length was noticeable.

5.5 Crack evolution on concrete and failure modes

No visible cracks were observed until the specimen lost its ability to support any additional load (F_{max}). After peak load the specimens presented a softening sliding response. The specimens strengthened with a steel bar of 8 mm diameter (S1) presented bond failure at the steel/adhesive interface. For the specimens with a steel bar of 12 mm diameter (S2), at peak load, some radial and circumferential cracks started being visible due to concrete fracture, followed by a decrease of the pull-out force with the increase of the pullout displacement of the steel bar. All the specimens of this series presented a mixed failure mode composed of debond at adhesive/concrete or steel/adhesive interfaces and concrete fracture due to the formation of a concrete cone.

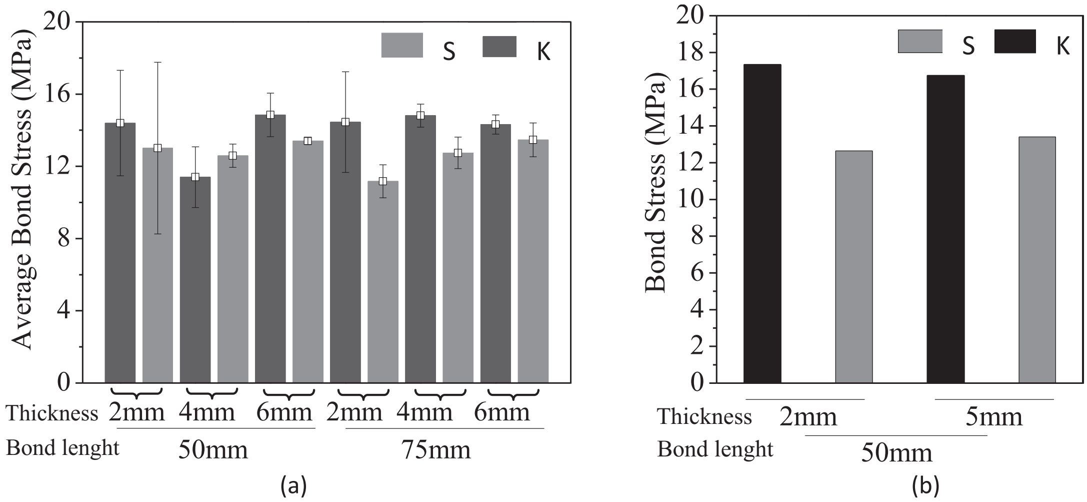
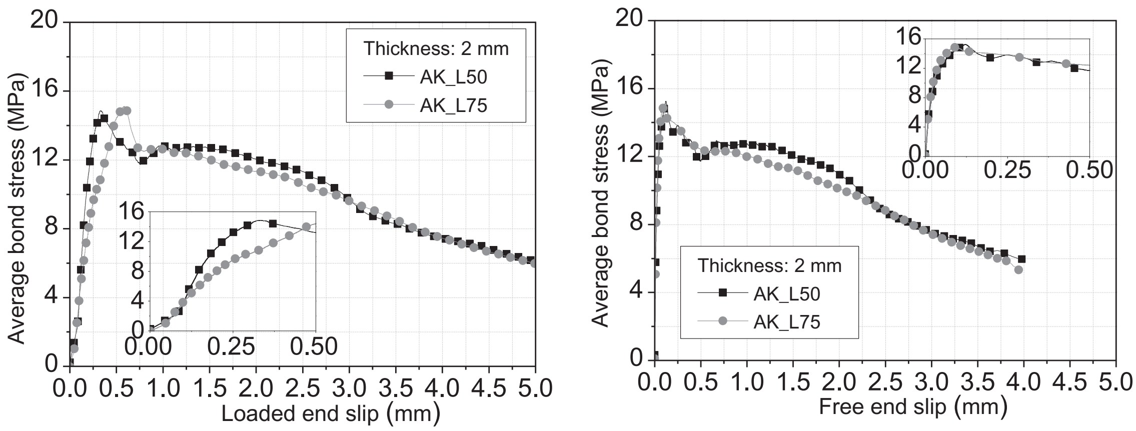


Figure 7 - Resume of the tested specimens: (a) S1 and (b) S2.



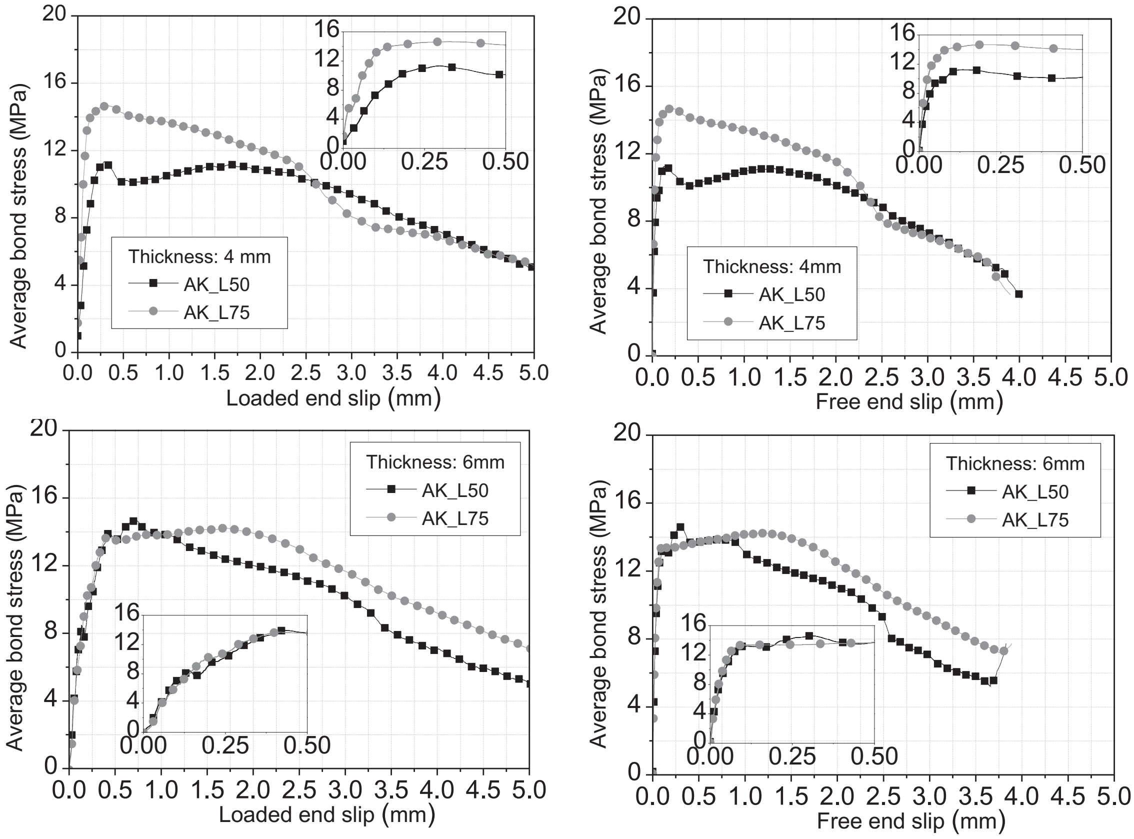
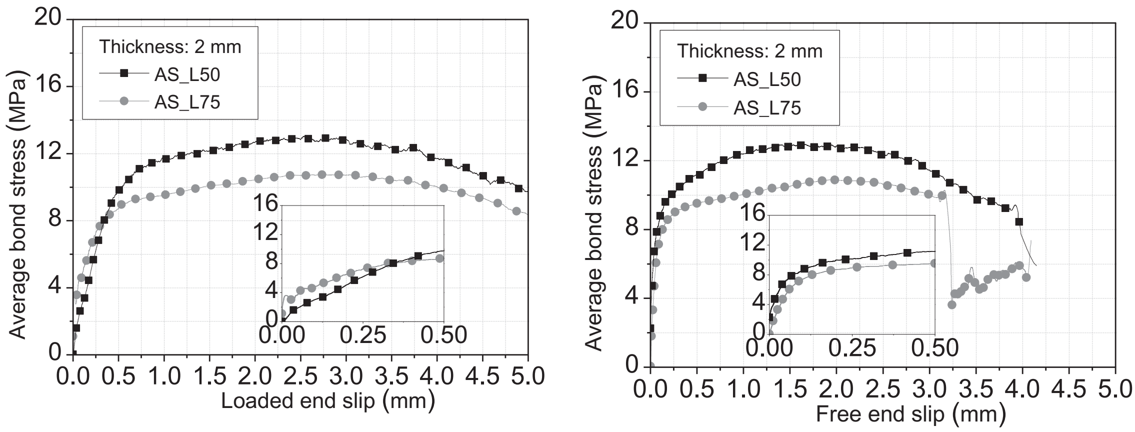


Figure 8 - Influence of the bond length on the average bond stress vs slip at the loaded and free ends for the specimens with Sikadur adhesive and bar diameter of 12 mm.



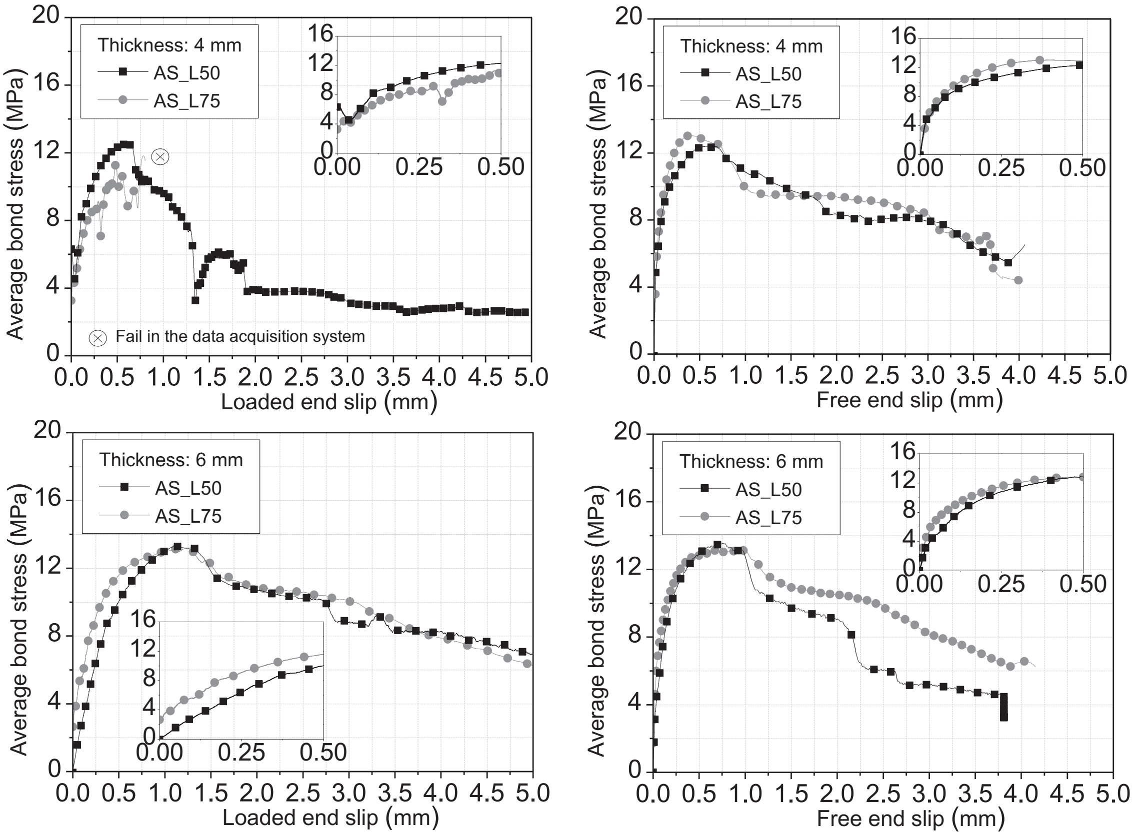
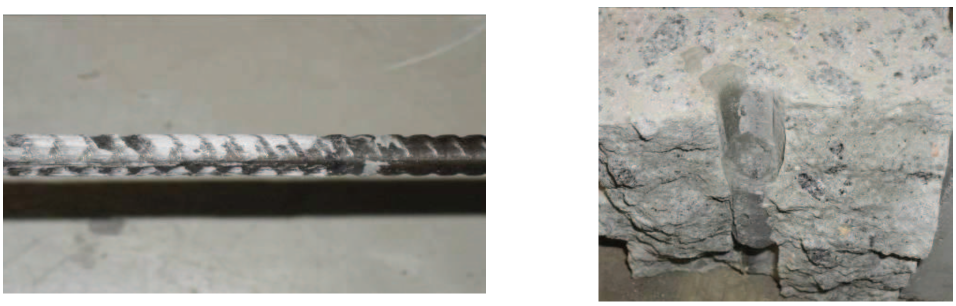
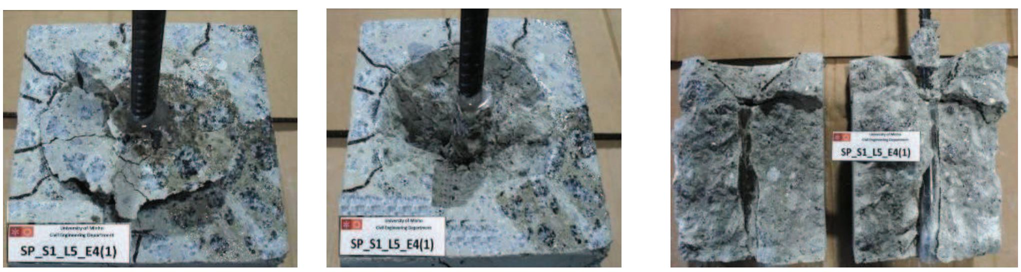


Figure 9 - Influence of the bond length on the average bond stress vs slip at the loaded and free ends for the specimens with S&P adhesive and bar diameter of 12 mm.



(a)



(b.1)

(b.2)

Figure 10 - Typical bond failure in the steel/adhesive interface (a) and mixed bond failure for E (b.1) and S (b.2) bond adhesives.

6. CONCLUSIONS

In the present study, a comprehensive experimental program of pullout tests was carried out, where the influence on the bond behavior of the following parameters was assessed: modulus of elasticity of types of epoxy-based adhesives; layer thickness (2 mm and 5 mm when using strengthening bars of 8 mm diameter; 2 mm, 4 mm, and 6 mm for the steel bars of 12 mm diameter) and the adhesive bond lengths (50 mm and 75 mm). Based on the results of this experimental program the following conclusions can be drawn:

(i) The bond behavior between bars and concrete depends on the type of adhesive chosen for the strengthening system;

(ii) With the values adopted for the anchorage length and for the adhesive layer thickness, the bond strength is marginal affected, but this last property has increased with the Young's modulus of the adhesive; and

(iii) From the obtained results it seems that for the interval of values considered for the adhesive thickness, this thickness has no significant influence on the type of failure mode and on the average bond strength.

7. ACKNOWLEDGEMENTS

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